Prepared in cooperation with the Legislative Commission on Minnesota Resources

Analysis of Suspended-Sediment Concentrations and Radioisotope Levels in the Wild Rice River Basin, Northwestern Minnesota, 1973–98

Water-Resources Investigations Report 01–4192

U.S. Department of the Interior
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CONVERSION FACTORS

Multiply	By	To obtain
Millimeters (mm	0.0393	inch
Centimeter (cm)	0.393	inch
Square centimeters (cm^2)	0.154	square inches
Meter (m)	3.281	foot (ft)
Gram (g)	0.35	ounce (avoirdupois)
Gram per cubic centimeter (g/cm^3)	1	metric ton per cubic meter (t/m^3)
Liter (L)	0.264	gallon
Square kilometer (km^2)	0.3861	square mile (mi^2)
Cubic feet per second (ft^3/s)	0.0283	cubic meters per second (m^3/s)
Millibecquerels (mBq)	16.67	disintegrations per minute (dpm)
Millibecquerels (mBq)	37	picocuries (pCi)
Meters per kilometer (m/km)	10	percent slope
Centimeters per year (cm/yr)	100	centimeters per century
Metric ton per day (t/d)	1,000	kilograms

Radioactivity is reported in millibecquerels (mBq). A becquerel is one radioactive disintegration (decay) per second (dps). Activities are expressed on a dry-mass basis—millibecquerels per gram of dry sediment or soil (mBq/g). Inventories of radioisotopes are expressed as the amount of isotope contained in a vertical soil profile under a 1 cm^2 area, in millibecquerels per square centimeter (mBq/cm^2).

Analysis of Suspended-Sediment Concentrations and Radioisotope Levels in the Wild Rice River Basin, Northwestern Minnesota, 1973–98

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ABSTRACT

We examined historical suspended-sediment data and activities of fallout radioisotopes (lead-210 [^{210}Pb], cesium-137 [^{137}Cs], and beryllium-7 [^{7}Be]) associated with suspended sediments and source-area sediments (cultivated soils, bank material, and reference soils) in the Wild Rice River Basin, a tributary to the Red River of the North, to better understand sources of suspended sediment to streams in the region. Multiple linear regression analysis of suspended-sediment concentrations from the Wild Rice River at Twin Valley, Minnesota indicated significant relations between suspended-sediment concentrations and streamflow. Flow-adjusted sediment concentrations tended to be slightly higher in spring than summer-autumn. No temporal trends in concentration were observed during 1973–98. The fallout radioisotopes were nearly always detectable in suspended sediments during spring-summer 1998. Mean ^{210}Pb and ^{7}Be activities in suspended sediment and surficial, cultivated soils were similar, perhaps indicating little dilution of suspended sediment from low-isotopic-activity bank sediments. In contrast, mean ^{137}Cs activities in suspended sediment indicated a mixture of sediment originating from eroded soils and from eroded bank material, with bank material being a somewhat more important source upstream of Twin Valley, Minnesota; and approximately equal fractions of bank material and surficial soils contributing to the suspended load downstream at Hendrum, Minnesota. This study indicates that, to be effective, efforts to reduce sediment loading to the Wild Rice River should include measures to control soil erosion from cultivated fields.

INTRODUCTION

Soil erosion and sediment loading to streams are concerns in the Red River of the North Basin (RRB) in Minnesota, North Dakota, South Dakota, and Manitoba, Canada. Soil erosion may reduce cropland fertility. Agricultural drainage ditches fill with eroded sediment over time, and require costly ditch maintenance. High suspended-sediment concentrations can also adversely affect aquatic ecosystems (Waters, 1995). Water utilities that use water from the Red River of the North (Red River) as a source of drinking water must spend more to treat water that has high sediment concentrations. Lake Winnipeg, in Manitoba, receives most of its tributary sediment loading from the Red River. Eutrophication in southern Lake Winnipeg due to sediment and nutrients (some portions of which are originally sediment-bound) is a concern. To better understand the dominant sources of sediment—channel processes or upland soil erosion—to streams in the RRB, the U.S. Geological Survey (USGS) in cooperation with the Legislative Commission on Minnesota Resources studied soils and suspended sediments of the tributary Wild Rice River Basin of northwestern Minnesota.

The RRB is set in glacial-lake-bed, glaciofluvial, and morainal topography. Nearly all of the streams flow through glacial deposits or glacial lake-bed sedimentary deposits, and exhibit channel meanders, cut banks, and point bars, and often fairly turbid waters. Much of the RRB—particularly in the Red River Valley—is cultivated cropland, and soil erosion from cropland also contributes to the sediment load in streams. It is widely accepted that sediment sources in streams in such settings are comprised of sediment that originates both from eroded soil and from erosion of stream-bank sediments (Colby, 1963). The relative amounts from these two sources in a given stream is seldom known. It is important for natural resource managers to gain a better understanding of sediment sources, so that management efforts can be targeted accordingly.

The study objectives were to: (1) analyze suspended-sediment concentrations at stream sites within the Wild Rice River Basin for possible relations to streamflow, seasonality, and long-term trends, and calculate sediment loads; (2) determine the relative importance of soil erosion versus streambank erosion as potential sources of sediment to the Wild Rice River, based on activities of the fallout radioisotopes lead-210 (^{210}Pb), cesium-137 (^{137}Cs), and, secondarily, beryllium-7 (^{7}Be) in suspended sediments in transport and in potential sources; and (3) determine gross erosion rates from upland source areas using radioisotope analysis of soil cores from cultivated and undisturbed settings. This report describes results related to objectives (1) and (2). Objective (3), an analysis of soil-core isotopic inventories measured to determine historical upland erosion rates, is being addressed separately (C.J. McCullough,U.S. Geological Survey, written commun., 2001).

This report summarizes suspended-sediment concentration data collected during 1973–98. Radioisotope samples were collected during 1998. Sampling for isotopic activities was targeted toward runoff events, with minimal sampling during base flow.

Environmental setting

The Wild Rice River Basin (4,170 km^2) drains parts of three ecoregions (Omernik and Gallant, 1988; Stoner and others, 1993) (fig. 1). The headwaters are in the Northern Lakes and Forests ecoregion, which is predominantly forested land with lakes and minimal agriculture (mostly grazing). Stream slopes in this ecoregion average 0.95 m/km (Stoner and others, 1993). Farther west, the middle reaches span the North Central Hardwood Forest ecoregion, where the land cover is mixed forest, grazing, cropland, with some lakes. Stream slopes in this ecoregion are 0.5–1.7 m/km. Lower reaches of the basin are in the Red River Valley ecoregion, where about 80 percent of the land is cultivated. This ecoregion is the lake bed of Glacial Lake Agassiz, and has very low-gradient land surface with predominantly silt and clay soils. Numerous beach ridges from glacial Lake Agassiz, and a highly branched tributary system (fig. 1b) punctuate the transitional zone between North Central Hardwood Forest and Red River Valley ecoregions. In the Red River Valley ecoregion, an extensive network of drainage ditches (fig. 1b) augments natural drainage to more quickly remove excess water from cultivated fields.

Soils the Wild Rice River Basin are frozen in winter months, and probably have limited erodability during spring-snowmelt runoff, when the soils begin to thaw. Also, in early spring, soils have probably settled from fall tillage. Soils are potentially most erodible during late spring, after thawing, but before significant crop cover exists. Soils are less erodible during summer due to crop cover and during autumn because less precipitation typically falls than during spring.

Erodible cut banks are prevalent in the basin. The following are estimates of bank heights at cut bank areas along the Wild Rice River: along lower reaches of the river (from about 13 km [8 miles] east of Ada, Minn. to the confluence with Red River), bank heights are about 0.9–1.2 m (3–4 ft); farther upstream (about 9.6 km [8 miles] east of Ada to east of Twin Valley, Minn.), bank heights are about 7.5–12 m (25–40 ft); farther upstream (western Mahnomen County), bank heights are 3.3–4.5 m (10–15 ft); and in the headwaters (eastern Mahnomen County), bank heights are about 0.9–1.2 m (3–4 ft) (estimates from Curtis Borchert, Norman County Soil and Water Conservation District, oral commun., 2001). Separate estimates of typical bank heights are: 1.8–3.6 m (6–12 ft) near Ada, with some 3.6–4.4 m banks (12–14 ft); and maximum bank heights of 12 m (40 ft) near Twin Valley (Jerry Bents, Houston Engineering, Fargo, N. Dak., oral commun., 2001). Lastly, typical bank heights were estimated at 1.8–3.6 m (6–12 ft) downstream of Twin Valley; about 2.4 m (8 ft) upstream of Twin Valley; and 1.2–1.8 m (4–6 ft) farther upstream, in Mahnomen County (Henry Van Offelen, Minnesota Department of Natural Resources, oral commun., 2001). From these estimates, a typical height of eroded cut banks along the Wild Rice River is about 4 m, possibly as low as 2–3 m according to some estimates.

Hydrologic conditions during 1998 sampling

A very early snowmelt occurred in 1998. Large spring storms and runoff were followed by dry conditions from mid to late summer. May 1998 was unusually rainy, resulting in considerable runoff. May rainfall occurred prior to significant crop cover—any leaf growth that had started was insufficient to shelter soils from raindrop impact—thus, soils were highly susceptible to erosion. Heavy rains in early July fell on more settled soils and established crops.

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ANALYSIS OF HISTORICAL SUSPENDED-SEDIMENT DATA

Suspended-sediment data

Considerable data exist for the Wild Rice River at Twin Valley (site 05062500, fig 1a). During some years in the 1970's, approximately daily sediment samples were collected during open water season; less frequent samples were collected in the mid-1990's. Few historical sediment data exist for the Wild Rice River at Hendrum (site 05064000, fig. 1a); therefore, we collected additional samples at this site. Sediment samples, both historical and recent, were collected and analyzed by traditional USGS methods (Guy, 1969; Guy and Norman, 1970; Tornes and others, 1997). Sediment-concentration data were retrieved from the USGS water-quality data base (QWDATA) and from paper files. Many historical data exist in the USGS daily-values data base (ADAPS); however, daily data are typically smoothed to produce daily-average records, and rounded, removing some laboratory precision. Thus, raw data extracted from paper files were preferred for statistical analyses performed herein. The large historical data set for Twin Valley includes samples collected by several slightly different methods (single-vertical, multiple-vertical, equal-width-increment), and different sampling equipment. Data were analyzed without regard to specific sampling methods or equipment.

Relation to streamflow, season, and time

Background

Suspended-sediment concentrations are often related to streamflow. Higher stream velocities, which correspond to higher streamflows, are potentially more erosive and can carry greater sediment loads than slower-moving water. Also, soil erosion contributes sediment to overland runoff, and higher streamflows result from overland runoff compared to base

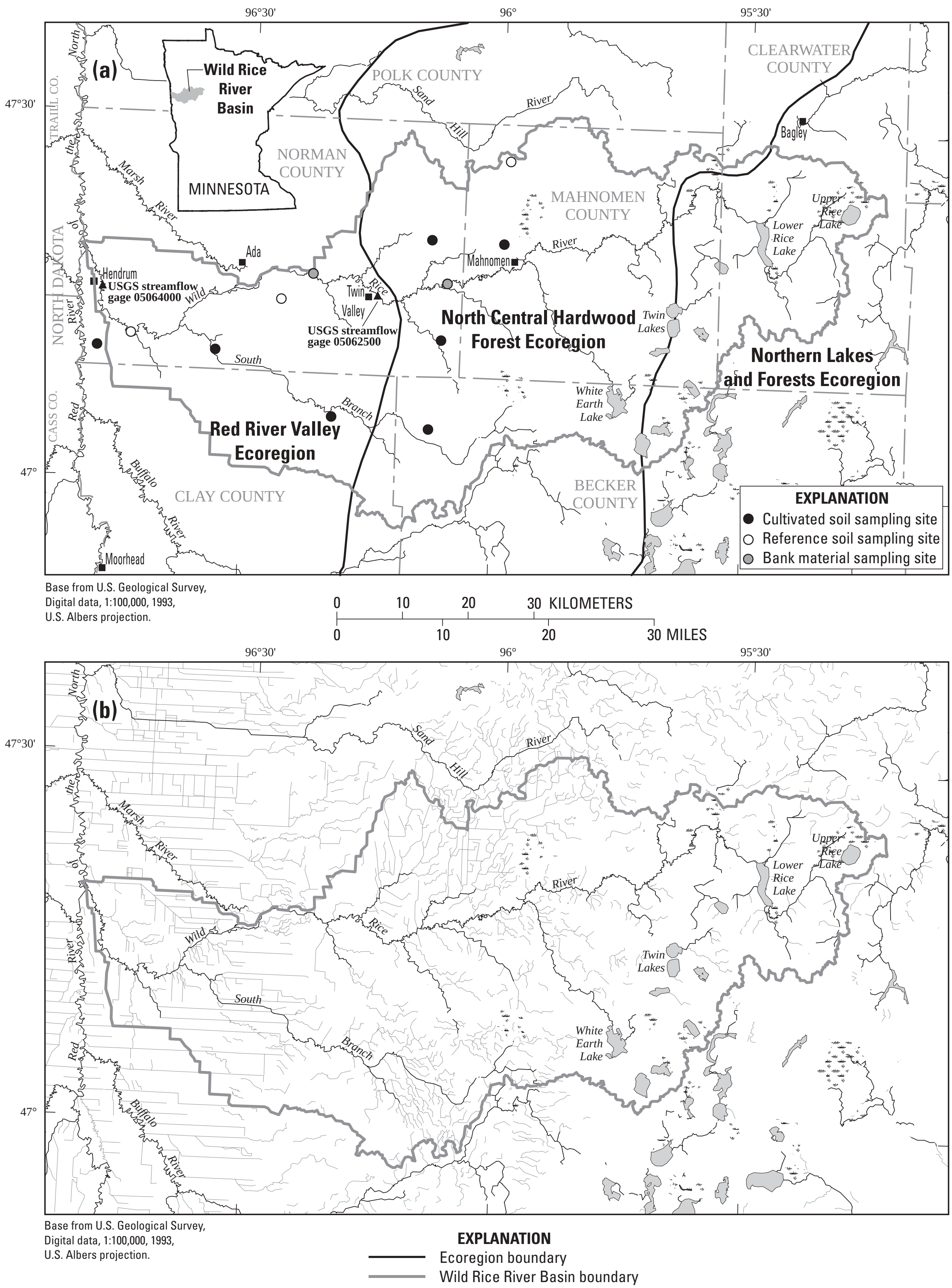

Figure 1. (a) Wild Rice River Basin, major tributaries, ecoregions, and location map. (b) detailed hydrography including ditches and minor tributaries. (Ecoregion boundaries from Omernik, 1987 and Stoner and others, 1993.)

flow. Often, both streamflow and suspended-sediment data for a site are approximately log-normally distributed. Thus, log-transformed concentration and streamflow data are typically used in data analysis.

Often, the sediment concentrations exhibit hysteresis with respect to streamflow—concentrations are higher during periods of rising stage, and lower during periods of falling stage during a single runoff event. Colby (1963, p. A23) notes that: “Peak concentration of fine material early in the runoff is consistent with the idea that loose soil particles at the beginning of a storm will be eroded by the first direct runoff of appreciable amount.” Typically in the Wild Rice River, multiple samples were not collected over single runoff events, so there are insufficient data to determine hysteresis effects in the Wild Rice River.

Seasonality in sediment data could be related to several physical factors: cropping practices, wind erosion, water erosion, and frozen soils during winter. In the RRB, typical cropland practice is: plant in the spring (winter wheat is planted in the fall), and harvest and till soil in the fall. Bare soil, susceptible to both wind and water erosion, covers large areas from fall until the next season’s crops grow. Fall months tend to be drier than growing season months, with few heavy rainstorms. Freezing and snow cover minimize, but do not eliminate, erosion during the winter. High winds erode snow and topsoil, which tend to be deposited in ditches and vegetated areas. A portion of winter-eroded soil, particularly that deposited in ditches, may be readily transported to streams. Wind erosion of soils may be more acute during spring months, particularly dry springs, than in winter because frozen soils are less erodible and runoff is uncommon during most winters in the RRB. These considerations combine to result in the greatest soil-erosion rates (from water erosion) expected during runoff events in the spring (before plant growth stabilizes the soils and crop canopy protects soils from the effects of precipitation) and autumn (after harvesting and tillage, when soils are most disturbed if rainfall is greater than normal. Conversely, the lowest soil erosion rates are expected during base flows of winter months, and possibly during mid-summer, when crop vegetation minimizes the erosive effects of direct impact of raindrops. Hence, seasonality is considered in data analysis.

Long-term trends in sediment concentrations could be caused by large-scale changes in tillage practices; changes in rainfall-runoff relations due to changes in land use; and construction of dams that would tend to trap sediments. Therefore, time is included in data analysis to assess long-term (multi-year or decadal) trends.

Regression model and results of sediment analysis

Data from 913 suspended-sediment samples from the Wild Rice River at Twin Valley were analyzed in detail (maximum of one sample per day). Only 35 values exist for the Wild Rice River at Hendrum; therefore detailed exploratory data analysis was not performed for data from that station. Instead, it was assumed that the form of the regression model developed for the Twin Valley station (discussed below) was suitable for the Hendrum station. Because of the limited data for the Hendrum station, model validity cannot adequately be assessed, and load estimates from that site are concomitantly less certain.

Trends in suspended-sediment concentration with respect to streamflow, season, and time were analyzed with multiple linear regression analysis, using the REG procedure of SAS software (version 8, SAS Institute, Cary, N.C.). The regression model is expressed by the following equation:

$$\log_{10}S = a + b\log_{10}Q + c(\log_{10}Q)^2 + dQ^{0.5} + e\,\mathrm{sine}(2\pi t) + f\,\mathrm{cosine}(2\pi t) + gt + \varepsilon \quad (1)$$

where $\log_{10}$ is the base-10 logarithm function;

S is suspended-sediment concentration, in milligrams per liter;

Q is streamflow, in cubic meters per second;

t is time, in years;

ε is the error, or residual, which is the difference between the predicted value and an individual observation; and

a-*g* are regression coefficients.

The trigonometric functions (sine and cosine) of time account for the seasonal component of variability in sediment concentrations. Significant temporal trends are indicated if the time term (t) is significant (that is, if the coefficient *g* differs significantly ($\alpha_{\text{cri t}} = 0.05$) from zero). Residuals from a simpler model, excluding the $(\log_{10}Q)^2$ and $Q^{0.5}$ terms, exhibited heteroscedasticity (changing variance over the range in $\log_{10}Q$ values); these terms were therefore included. Exclusion of the $Q^{0.5}$ term resulted in overprediction of loads at the highest load values, thus overestimating annual loads for two high-flow years for which nearly daily sediment samples were collected (1978–79).

An attempt to account for hysteresis, by comparing suspended-sediment concentrations to the change in gage height over a four-hour period prior to sampling, produced no significant relation. Thus, no term to account for hysteresis was included in the regression equation.

The streamflow component of equation 1 (plotted as the smooth line in fig. 2a) fits log-transformed sediment concentrations reasonably well, although there is considerable variability in the sediment data. There is a significant, but small seasonal influence on suspended-sediment concentrations: flow-adjusted values [residuals from regression of $\log_{10}S$ versus $\log_{10}Q$, $(\log_{10}Q)^2$, and $Q^{0.5}$] are greatest in the spring and early summer, and are least during late-summer through autumn (fig. 2b).

To analyze for temporal trends, data were trimmed to a maximum of one sample per week (by selecting the first sample in a one-week period), resulting in 220 samples used in the analysis. This was done for two primary reasons: (1) the sampling frequency was much greater during the 1970’s than 1990’s, and spurious trends can result from unbalanced data sets, and (2) spurious “significant” trends can also result from large numbers of samples. No significant temporal trends were observed; therefore, time (t) was removed from the regression analysis for load computations. The other regression coefficients (*a*-*f* in equation 1) were nearly unchanged regardless of which data set (all data or trimmed data set) was used.

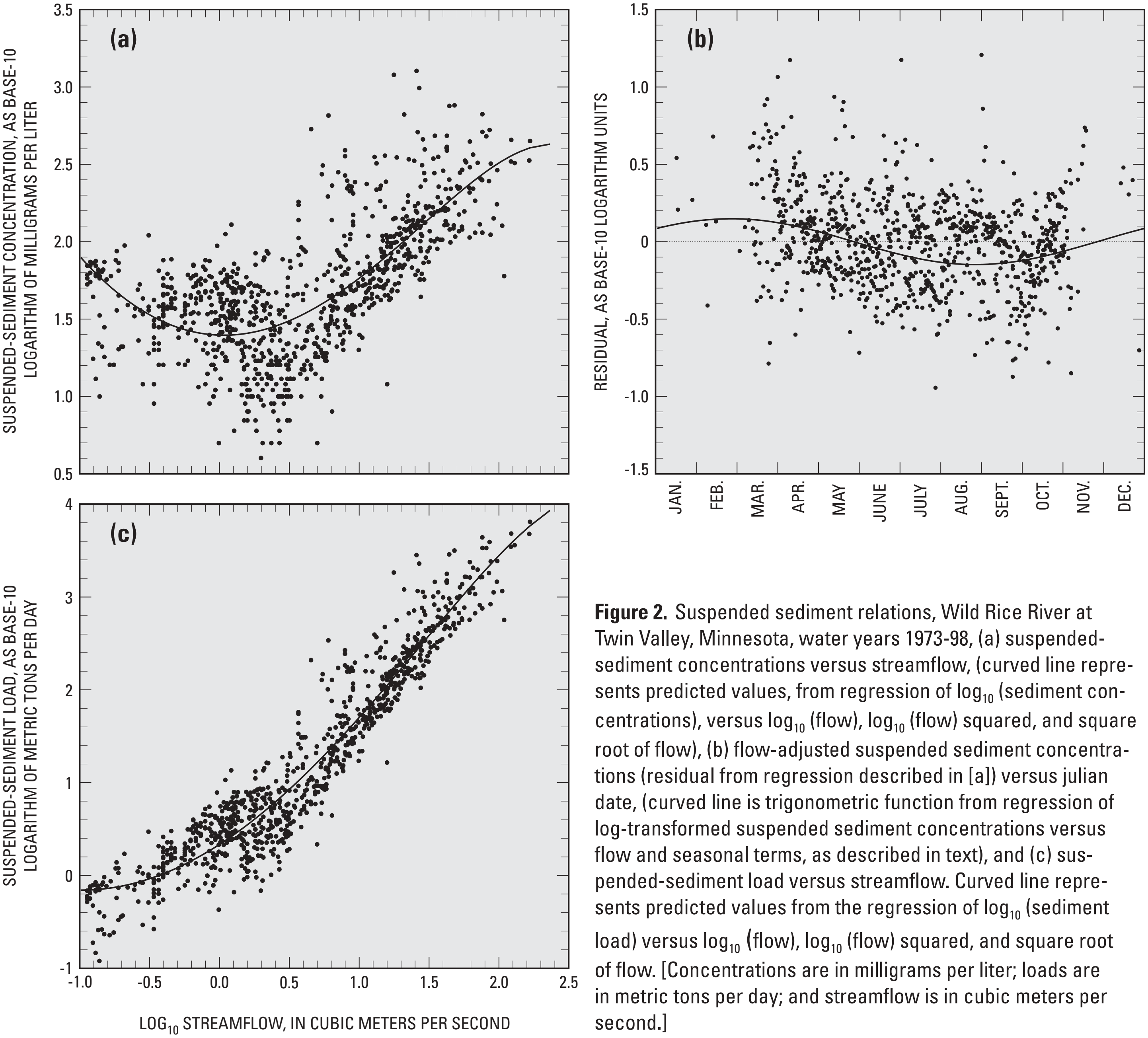

Figure 2. Suspended sediment relations, Wild Rice River at Twin Valley, Minnesota, water years 1973-98, (a) suspended-sediment concentrations versus streamflow, (curved line represents predicted values, from regression of $\log_{10}$ (sediment concentrations), versus $\log_{10}$ (flow), $\log_{10}$ (flow) squared, and square root of flow), (b) flow-adjusted suspended sediment concentrations (residual from regression described in [a]) versus julian date, (curved line is trigonometric function from regression of log-transformed suspended sediment concentrations versus flow and seasonal terms, as described in text), and (c) suspended-sediment load versus streamflow. Curved line represents predicted values from the regression of $\log_{10}$ (sediment load) versus $\log_{10}$ (flow), $\log_{10}$ (flow) squared, and square root of flow. [Concentrations are in milligrams per liter; loads are in metric tons per day; and streamflow is in cubic meters per second.]

Sediment loads

A regression equation similar to equation 1 was used to calculate suspended-sediment loads:

$$\log_{10}L = a + b\log_{10}Q + c(\log_{10}Q)^2 + dQ^{0.5} + e\text{sine}(2\pi t) + f\text{cosine}(2\pi t) + \varepsilon \quad (2)$$

where L = suspended-sediment load (the product of measured concentration and daily mean streamflow, converted to metric tons per day), and the time term has been dropped. This approach produces regression estimates of log-transformed loads (fig. 2c). Loads were calculated using the program Estimator (version 96.04 and Estimator2000; written by Timothy Cohn, U.S. Geological Survey), which uses the minimum variance unbiased estimator (MVUE) to correct for back-transformation bias from log space to linear space (Cohn and others, 1992; Cohn and others, 1989; Helsel and Hirsch, 1992).

Regression-predicted loads were calculated using daily mean flow for each gaging station. Predicted daily loads were then summed over the entire year to produce estimates of annual sediment loads. Annual loads of suspended sediment (fig. 3) vary greatly from year to year, as expected from the highly variable flow conditions.

The mean annual suspended-sediment load for water years 1973–98, excluding years for which no flow data exist (denoted by “nd” in fig. 3), is 31,500 metric tons per year at Twin Valley, and 60,000 metric tons per year at Hendrum. Sheet erosion of soil from agricultural

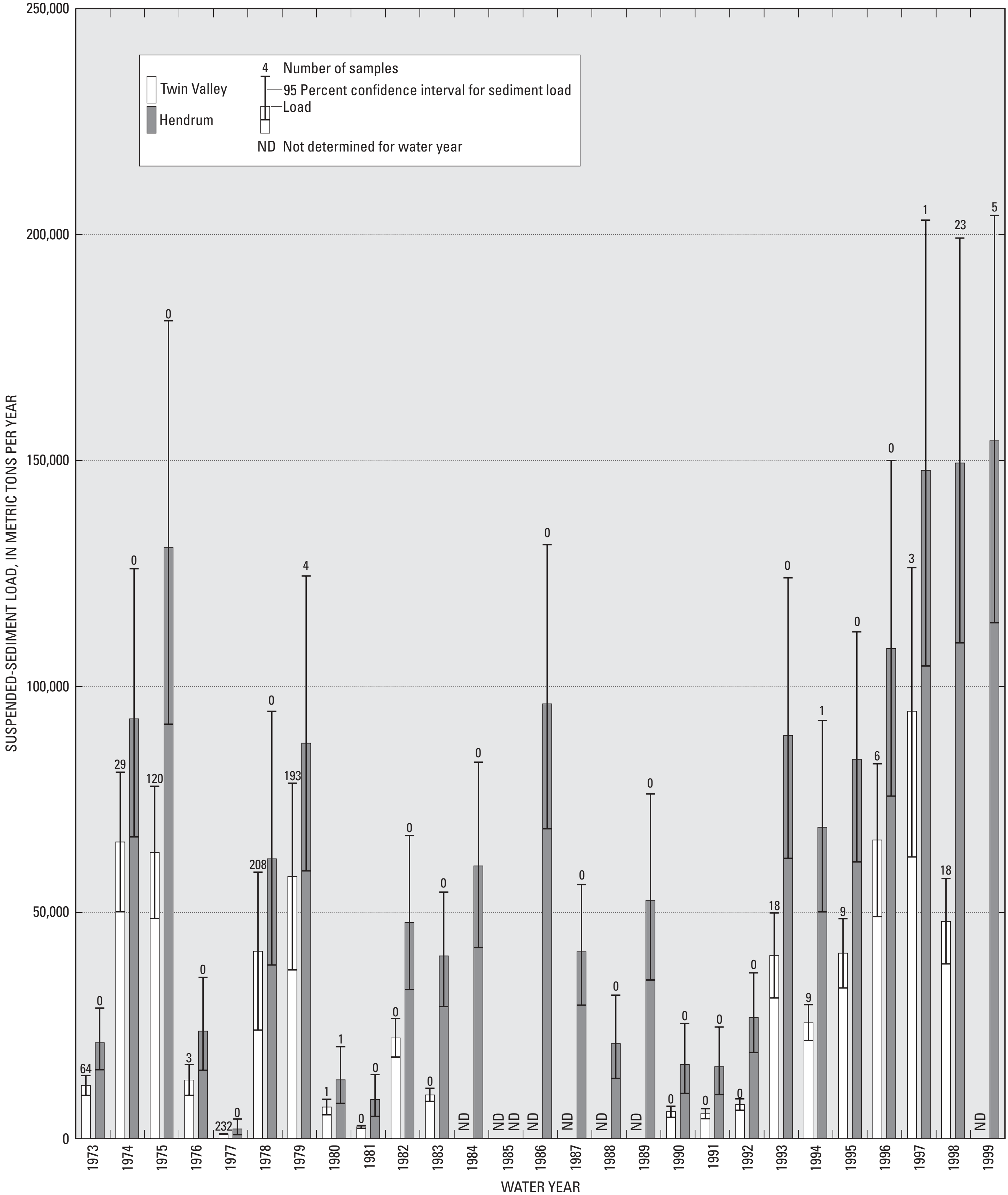

Figure 3. Estimated annual suspended-sediment loads, Wild Rice River at Twin Valley, Minnesota, and at Hendrum, Minnesota.

fields would have to erode, on average, the upper 0.022 mm/yr of soil (2.2 mm per century) to supply the mean sediment load at Twin Valley, and 0.025 mm/yr (2.5 mm per century) to supply the mean sediment load at Hendrum. This estimate results from dividing the sediment load (t/d) by average bulk density (1.2 g/cm^3, or 1.2 metric tons per m^3); then dividing by the area of agricultural land (drainage area at Twin Valley = 2,405 km^2, 50 percent of which is agricultural, including cropland and pasture (Lorenz and Stoner, 1996); drainage area at Hendrum = 4,038 km^2, and assuming the same percentage of agricultural land as the basin upstream of Twin Valley, although the western portion of basin is more highly cultivated).

A parallel estimate can be developed if one assumes all suspended sediment in the river came from streambank erosion. Assuming a mean bank height of 4 m, channel length of 341 km (the sum of all channel lengths in the Wild Rice River Basin fig. 1a), and cut banks occurring only on one side of the river, then net bank erosion of 3.7 cm/yr (3.7 m per century) would be required to supply the sediment load at Hendrum. That is, entire vertical sections of erodible cut bank would recede, or erode, by an average of 3.7 cm/yr, with no redeposition, to supply the sediment load. If bank erosion occurring along 25 percent of the river banks, then approximately 15 cm/yr (or 15 m per century) (3.7 ÷ 0.25) of net bank erosion would be required to supply the sediment load.

Delivery (or yield) of sediment from large watersheds is known to be a small fraction of total erosion (Walling, 1983), although that fraction varies widely among watersheds. Much of the eroded sediment is redeposited on the land surface (soils) and in the channel environment, including flood plain, point bars, and stream-bottom sediments (soils and bank materials). Assuming a delivery ratio of 0.1 (10 percent of eroded material is delivered from the basin as suspended sediment, and 90 percent is redeposited), which is reasonable for watersheds larger than 1,000 km^2 (Walling, 1983), then total erosion of soils of about 25 mm (2.5 cm, or about 1 inch) per century would be required, whereas total horizontal bank cutting of 37–150 m per century would be required. Thus, net rates of erosion (total erosion minus redeposition) needed to supply the annual sediment loads in the Wild Rice River are quite small if soil is the dominant source. Total rates of bank erosion required to supply net delivery of suspended sediments are very high if one assumes that about 90 percent of eroded sediment is redeposited in the channel environment. Redeposition of sediments from bank erosion would be minimal for fine (<63 µm) sediments, but could be substantial for coarser sediments (>63 µm)

RADIOISOTOPE LEVELS OF SEDIMENTS

Background on use of radioisotope methods

Radioisotope methods offer promise in soil erosion and sediment-source studies, and researchers continue to refine appropriate models. Since early studies by Ritchie and others (Ritchie and McHenry, 1975; Ritchie and others, 1974), fallout radioisotopes have been used increasingly in soil erosion and sedimentation studies. Early studies relied exclusively on ^{137}Cs, whereas more recently, various radioisotopes have been used, sometimes in conjunction with other geochemical measurements.

The basis for the use of fallout radioisotopes in sediment studies can be summarized as follows: ^{210}Pb, ^{137}Cs, and ^{7}Be are deposited on the earth's surface as atmospheric fallout at rates that are thought to be spatially uniform, within a limited geographic range (similar latitude and annual precipitation). These isotopes sorb to soil particles and decay at rates described in terms of half-life ($t_{1/2}$), which is the time that it takes for one-half of an isotope to decay producing a daughter product. Because decay of these fallout isotopes is rapid, with respect to geologic time scales, deeper soils are essentially devoid of fallout isotope activities. The areal input of these isotopes can be measured in soil profiles taken from areas known to be non-erosional and non-depositional (other than from the atmosphere). Comparing areal isotopic inputs to measured isotopic inventories in study soil profiles and understanding how these inventories change in soil profiles can be used to assess redistribution of surficial soils, and to assess sources of suspended sediment, assuming appropriate end members can be identified.

Sources of isotopes

^{210}Pb ($t_{1/2}$=22.3 yr) is a naturally occurring isotope, formed in the uranium-238 decay series (Turekian and others, 1977). Radium-226 (^{226}Ra), also a member of this series, decays to form radon-222 (^{222}Rn, $t_{1/2}$=3.82 d), a gaseous species. A portion of ^{222}Rn escapes from the earth's crust and is distributed in the atmosphere, where it quickly decays through a series of short-lived isotopes to form ^{210}Pb. ^{210}Pb is effectively removed from the atmosphere by wet and dry deposition (Baskaran and others, 1993). Because not all the ^{222}Rn escapes the earth's crust before it decays, a portion of the ^{210}Pb present in the earth's crust (for example, soil and sediment) is formed *in situ* as a product of this decay series. This portion, termed supported ^{210}Pb, has an activity equal to that of ^{226}Ra, owing to a secular equilibrium between ^{226}Ra and its daughter products. Excess (unsupported) ^{210}Pb is that portion of ^{210}Pb that is derived from atmospheric fallout (from decay of atmospheric ^{222}Rn gas and subsequent fallout of the daughter isotope). Subtracting measured ^{226}Ra activity from measured (total) ^{210}Pb activity yields excess ^{210}Pb activity.

^{137}Cs ($t_{1/2}$=30.2 yr) is formed as a by-product of thermonuclear reactions, and was introduced to the atmosphere primarily from above-ground nuclear device testing. Significant inputs of ^{137}Cs into the atmosphere began in 1954, peaked in 1963, and afterwards decreased sharply (Delaune and others, 1978; He and others, 1996) due to the atmospheric test ban treaty. Since 1968, atmospheric ^{137}Cs deposition has been negligible. Fallout of ^{137}Cs resulting from the Chernobyl explosion of 1986 was mainly limited to Europe (Antonopoulos-Domis and others, 1995; Owens and others, 1996; Ritchie and McHenry, 1990; Rosén and others, 1998).

^{7}Be is a short-lived ($t_{1/2}$=53.3 d), naturally occurring isotope produced by cosmic ray bombardment of oxygen and nitrogen in the atmosphere (Lal and others, 1958; Rangarajan and Gopalakrishnan, 1970). Like ^{210}Pb and ^{137}Cs, ^{7}Be strongly sorbs to particles in the atmosphere and rapidly falls out to the earth's surface (Todd and others, 1989; and references therein).

The behavior of ^{210}Pb, ^{137}Cs, and ^{7}Be is well documented (reviewed by Ritchie and McHenry, 1990; Todd and others, 1996; Wallbrink and Murray, 1993; Walling and others, 1999). Wet deposition is the predominant fallout mechanism, although some dry deposition of aerosol-bound radioisotopes occurs. Rates of fallout, therefore, are highly dependant on precipitation patterns. Deposition rates, and hence areal burdens in soils (inventories), of the longer-lived isotopes, ^{210}Pb and ^{137}Cs, are considered to be regionally uniform because short-term variability in precipitation (deposition) is smoothed over time by many precipitation events. Conversely, ^{7}Be may exhibit considerable spatial variability within a region because individual precipitation events are not evenly distributed, and the isotope decays rapidly.

Although small amounts of these fallout isotopes may be taken up by plants and removed with harvested crops, most of the deposited isotope remains in the particle phase. The primary mechanisms by which isotopic activities are diminished are assumed to be radioactive decay, dilution by limited penetration of surficial activities into the soil column, and erosion of the soil from a site.

The source functions for the three isotopes, with respect to their decay rates, are quite different. ^{210}Pb deposition is thought to be relatively constant over time (it is naturally replenished in the atmosphere via degassing of ^{222}Rn). The ^{210}Pb inventory is large and the decay rate is slow, relative to seasonal variability in ^{210}Pb deposition. ^{137}Cs can be viewed as a pulse input in the early 1960's. Its inventory is decreasing over time, with minute new inputs. The short half life of ^{7}Be, combined with seasonally varying fallout rates, results in strong seasonal dependence of soil-bound ^{7}Be activities.

Behavior of ^{210}Pb, ^{137}Cs, and ^{7}Be in soils

All three isotopes strongly sorb to soil and suspended-sediment particles (Hawley and others, 1986; Jenne and Wahlberg, 1968; Ritchie and McHenry, 1990; Wallbrink and Murray, 1993; Walling and others, 1999), and can act as tracers of eroded surficial soils. In undisturbed soils, excess ^{210}Pb and ^{137}Cs activities extend to soil depths of about 5–40 cm, depending on soil conditions, with peak activities typically in the upper few centimeters (Olsen and others, 1985; Wallbrink and Murray, 1993, 1996a; Walling and Quine, 1994; Walling and Woodward, 1992). In contrast, ^{7}Be tends to be detected only in the upper 1–2 cm of undisturbed soils (Wallbrink and Murray, 1993, 1996b); it's rapid decay rate precludes substantial downward migration.

In cultivated settings, plowing evenly distributes ^{210}Pb and ^{137}Cs throughout the plowed layer, typically the upper 20 cm; activities rapidly diminish at greater depths (Walling and Quine, 1994; Walling and Woodward, 1992). ^{7}Be is not long-lived enough to become homogenized in the plow layer from annual plowing. Even in cultivated settings, ^{7}Be is typically detected only at the surface, with highest activities in the upper 1–2 mm.

Radioisotopes have been used extensively to assess upland soil erosion from agricultural settings (reviewed in Ritchie and McHenry, 1975; Ritchie and McHenry, 1990; Walling and Quine, 1992, 1994). Long-term fallout of radioisotopes should be spatially uniform within a region—that is, where latitude and annual precipitation do not vary significantly. Hence, the inventory of excess ^{210}Pb and ^{137}Cs in undisturbed soils should be regionally uniform. Herein, inventory is defined as activity per unit area of a soil column (in mBq/cm^2), and is determined as the product of activity (mBq/g) and the dry mass per unit area (g/cm^2), summed over the depth of detectable isotope activities.

Inventories are useful for comparing isotopic data for reference (undisturbed) sites within a region.Whereas activity-depth relations may vary somewhat among sites, depending on soil characteristics, reference inventories should be relatively uniform within a region. Reference inventories are typically determined by analyzing radioisotope profiles in several soil cores from undisturbed settings. In disturbed settings (cultivated fields) isotopic inventories vary considerably depending on whether a specific core is from an erosional or a depositional setting. Erosional settings generally contain isotopic inventories less than the reference inventory, because some soil (and soil-bound radioisotope) has been eroded from the site. Depositional settings generally contain isotopic inventories greater than the reference inventory. Radioisotope inventories that are nearly equal to the reference inventory indicate little net movement of soil—either total movement is minimal, or erosion is balanced by deposition of soils that were eroded upslope from the core site.

Radioisotope study approach

Most radioisotope studies of soil erosion and fluvial sediment sources have been on small watersheds—many at the scale of a single farm field—allowing detailed, spatially focused measurements of radioisotope inventories to assess net erosion rates of fields. This study, in contrast, attempts to describe sediment sources on the scale of a 4,038 km^2 basin. Thus our approach was to compare radioisotope activities in suspended sediments with those of potential source areas (soil erosion from cultivated land and bank erosion), by comparing radioisotope inventories from reference cores to soil cores collected along hill slope transects from selected field sites across the basin (C.J. McCullough, U.S. Geological Survey, written commun., 2001).

Radioisotope activities of suspended sediments reflect the weighted average of the radioisotope levels of sediments from each type of source area. Two potential sources of sediment would be expected to predominate in the Wild Rice River Basin: eroded soil from cultivated farm land and eroded streambank sediments. Both sources are known to occur, but the relative magnitude of soil erosion versus bank erosion in the Wild Rice River Basin is unknown. Resuspension of stream-channel deposits may occur, but the source of channel deposits is presumed to be predominantly eroded sediment from soil or bank material. Soil erosion in grassland, forest, pasture, and wetlands is negligible. Within the basin, there is extensive cultivation, particularly in the central and western portions. Cut banks—as high as

12 m in some reaches—evidencing bank erosion are prevalent on the tributaries and main stem of the Wild Rice River.

Surficial cultivated soils would be expected to contain measurable quantities of excess ^{210}Pb and ^{137}Cs unless the inventory at a site has been eroded away completely. Bank material is assumed to contain excess ^{210}Pb and ^{137}Cs only in the upper 5–40 cm. With that assumption, and assuming erosion of a 4-m high cut bank—an estimated average for the river—then, the isotope activities from bank erosion would be diluted by a factor of 10–80 for a vertically eroded bank. ^{7}Be activities, contained in the upper 1–2 cm, would be diluted by a factor of 200–400 for a 4-m cut bank. Suspended sediments in transport should have isotopic activities similar to surficial soils if soils are the dominant sediment source; should be highly diluted (likely undetectable) if bank erosion is the dominant sediment source; or reflect modest dilution of soil-bound isotopic activities if the two sources are approximately equal in importance.

Sampling methods

Bulk quantities (tens of grams) of suspended sediment were separated from stream water via continuous-flow centrifugation. Water was pumped from near the center of the channel from the downstream side of a bridge, from about 0–0.5 m below stream surface, with a submersible centrifugal pump. Water was forced, through Tygon tubing, into an Alfa-Laval MAB-103B centrifuge at a rate of 4 L/min. Near-surface pump deployment likely excluded a portion of large-diameter particles (heavier sands), which preferentially travel near the streambed-water interface. Detailed descriptions of a comparable Alfa-Laval centrifuge have been given by Ongley and Thomas (1989) and Horowitz and others (1989). Horowitz and others (1989) determined that the Alfa-Laval centrifuge recovered 94–99 percent of inflowing suspended sediment. Following sampling, bulk sediment was transferred from the centrifuge bowl using a stainless steel scraper, into polypropylene jars (Nalgene). Internal surfaces (bowl and discs) were thoroughly cleaned of sediment between uses, using tap water.

Surficial soil samples were collected by scraping the upper 1 cm of soil into polyethylene bags. The sample locations were adjacent to cores collected for radioisotope inventories and soil morphology (Carolyn McCollough, U.S. Geological Survey, written commun., 2001), which were located along a hill slope sequence at the summit, shoulder, backslope, footslope, and toeslope when these positions were determinable. Sampling points were determined by observing changes in slope and surface soil color. All the samples, except the reference sites, were taken after harvest and fall tillage on fields used for wheat, soybeans, or sugar beets. Reference cores were collected for two purposes: (1) to compare with isotopic inventories determined on soil cores from cultivated settings (Carolyn McCullough, U.S. Geological Survey, written commun., 2001), and (2) to be representative of potentially erodible bank material. Reference cores were sampled with a truck-mounted, hydraulic powered Giddings probe (model GSRP-S-M), equipped with a 4.44-cm (1.75-inch) diameter, 122-cm long coring tube and a 5.1-cm quick relief bit. Core samples were collected and stored in Zero-Contamination tubes (Giddings Machine Co., Fort Collins, Colo.) with plastic liners. Reference sites were unused and supposedly undisturbed areas of cemeteries in the basin. Reference cores were assumed to represent bank-sediment isotopic levels. In addition, two cores were collected from streambanks using a stainless steel knife to transfer sediment to polypropylene jars. Bank-material cores were only analyzed (for two depth increments from each core, to confirm that surficial and deeper isotopic levels were not anomalous; table 1). Soil coring was conducted during the fall, after crops were harvested. During the fall, soils are typically drier (and thus accessible by truck) than during the spring, and this time is least disruptive to landowners.

In cultivated settings, the longer-lived fallout isotopes (^{210}Pb and ^{137}Cs) were assumed to be uniformly distributed in the upper 20 cm, due to mixing from annual plowing. Thus, surface activities are presumed to not vary greatly before and after a given year's tillage. In contrast, the short-lived ^{7}Be isotope is concentrated within the upper 1 cm (Wallbrink and Murray, 1996b), and decays too rapidly to be measurably distributed in the plow layer. Because soil samples were collected after fall tillage, surface ^{7}Be activities may have been diluted by as much as 20-fold (assuming uniform mixing in the plow layer).

Laboratory analysis of radioisotopes

Bulk sediment and soil samples were analyzed for radioisotopes at the Freshwater Institute, Department of Fisheries and Oceans, in Winnipeg, Manitoba. Six to eighteen grams of dried sediment were sealed in 60 x 15 mm plastic petri dishes, aged for 30 days, and counted for 48 hours each on a gamma spectrometer equipped with Ge (Li) [germanium(lithium)] or HPGe (hyperpure germanium) coaxial detectors, for the determination of ^{137}Cs and ^{226}Ra (Joshi, 1987) and ^{7}Be and potassium-40 (^{40}K). Sample activities were corrected for counting efficiencies, which were calculated using National Institute of Standards and Technology (NIST) standard reference material (SRM) spiked clay, soil and sediments. Counting efficiencies were also cross-checked through participation in the Environmental Measurements Laboratory Quality Assurance Program.

One- to three-gram samples of dried sediment were leached with 6-normal hydrochloric acid in the presence of an added polonium-209 tracer. Polonium was autoplated onto a silver disc (Flynn, 1968), which was then counted for 48 hours on an alpha spectrometer to determine ^{210}Pb from its polonium-210 daughter. ^{226}Ra was determined by the radon de-emanation technique (Mathieu, 1977; Wilkinson, 1985). Excess ^{210}Pb was determined in each sample by subtracting the ^{226}Ra activity from the total ^{210}Pb activity. All activities are corrected to the sampling date.

Radioisotope levels of sediments

All suspended-sediment samples had excess ^{210}Pb, and nearly always had measurable activities of ^{137}Cs (table 2). Mean activities of each isotope were slightly higher at the downstream site (Hendrum), and could reflect greater inputs of fine-grained sediments from the Red River Valley ecoregion. Activities of excess ^{210}Pb

Table 1. Radioisotope activities and inventories from reference cores in the Wild Rice River Basin.

[Raw data, with counting errors, are reported by Carolyn McCullough, U.S. Geological Survey, written commun., 2001.; n.d., not detected; --, not calculated or measured; (*), sample exceeded holding time for ^{7}Be; cm, centimeter; g, gram; mBq, millibecquerel; cm^2, square centimeter]

Sample identification	Depth increment (cm)	Dry mass/unit area (g/cm^2) (increment)	Dry mass/unit area (g/cm^2) (cumulative)	Excess ^{210}Pb activity (mBq/g)	Excess ^{210}Pb inventory (mBq/cm^2)	^{137}Cs activity (mBq/g)	^{137}Cs inventory (mBq/cm^2)	^{7}Be activity (mBq/g)	^{7}Be inventory (mBq/cm^2)
Core Identification: Reference Core 5-1, Landstad Church, 47°11'51" North 96°43'57" West									
R5-1-2	0-2	1.32	1.32	86.1	113.2	29.5	38.7	31.9	42.0
R5-1-4	2-4	1.80	3.12	45.9	82.7	27.4	49.3	n.d.	--
R5-1-6	4-6	1.71	4.83	23.4	40.0	19.5	33.3	n.d.	--
R5-1-8	6-8	1.77	6.60	14.1	25.1	16.8	29.8	n.d.	--
R5-1-10	8-10	2.41	9.01	10.5	25.3	11.6	27.8	n.d.	--
R5-1-12	10-12	1.89	10.90	7.9	14.9	7.7	14.5	n.d.	--
R5-1-14	12-14	2.17	13.07	n.d.	--	4.7	10.3	n.d.	--
R5-1-16	14-16	2.06	15.13	n.d.	--	3.4	7.1	n.d.	--
R5-1-18	16-18	2.17	17.30	n.d.	--	2.0	4.2	n.d.	--
R5-1-20	18-20	2.64	19.94	n.d.	--	1.5	4.0	n.d.	--
R5-1-24	20-24	3.76	23.70	n.d.	--	n.d.	--	n.d.	--
R5-1-28	24-28	5.06	28.76	n.d.	--	n.d.	--	n.d.	--
R5-1-32	28-32	4.00	32.76	n.d.	--	n.d.	--	n.d.	--
R5-1-36	32-36	5.48	38.24	n.d.	--	n.d.	--	n.d.	--
R5-1-40	36-40	5.30	43.54	n.d.	--	n.d.	--	n.d.	--
Cumulative (total) inventory					301.1		219.1		42.0
Core Identification: Reference Core 3-3, Skandinavia Church, 47°15'08" North 96°26'02" West									
R3-3-2	0-2	2.29	2.29	32.7	74.8	9.6	21.9	n.d.	--
R3-3-4	2-4	1.47	3.76	17.4	25.6	6.2	9.1	n.d.	--
R3-3-6	4-6	2.08	5.84	14.1	29.3	10.4	21.6	n.d.	--
R3-3-10	6-10	4.82	10.66	13.2	63.7	8.8	42.5	n.d.	--
R3-3-15	10-15	6.60	17.26	11.9	78.7	7.4	48.6	n.d.	--
R3-3-20	15-20	6.41	23.67	12.0	77.1	10.3	65.8	n.d.	--
R3-3-25	20-25	6.49	30.16	5.8	37.7	7.6	49.6	n.d.	--
R3-3-30	25-30	5.79	35.95	0.6	3.5	6.0	34.9	n.d.	--
R3-3-35	30-35	5.46	41.41	n.d.	--	n.d.	--	n.d.	--
Cumulative (total) inventory:					390.4		294.0		
Core Identification: Reference Core 6-2, Bejou, 47°27'06" North 95°59'00" West									
R6-2-2	0-2	1.99	1.99	40.1	79.9	5.7	11.3	n.d.	--
R6-2-4	2-4	2.25	4.24	19.8	44.5	6.1	13.7	n.d.	--
R6-2-6	4-6	2.29	6.53	10.2	23.4	3.7	8.4	n.d.	--
R6-2-10	6-10	4.66	11.19	5.4	25.3	3.4	15.8	n.d.	--
R6-2-14	10-14	4.97	16.16	n.d.	--	n.d.	--	n.d.	--
R6-2-18	14-18	5.18	21.34	0.4	2.1	n.d.	--	n.d.	--
R6-2-22	18-22	5.28	26.62	0.4	2.3	n.d.	--	n.d.	--
R6-2-26	22-26	4.99	31.61	2.0	10.2	n.d.	--	n.d.	--
R6-2-30	26-30	5.54	37.15	1.6	8.6	n.d.	--	n.d.	--
R6-2-34	30-34	5.35	42.50	n.d.	--	n.d.	--	n.d.	--
R6-2-38	34-38	5.26	47.76	n.d.	--	n.d.	--	n.d.	--
Cumulative (total) inventory:					196.4		49.3		
Core identification: Bank 1, 47°16'54" North 96°06'05"West									
Bank 1-10	0-10	--	--	77.8	--	34.4	--	(*)	--
Bank 1-40	35-40	--	--	n.d.	--	n.d.	--	(*)	--
Core identification: Bank 2, 47°17'19" North 96°22'17" West									
Bank 2-10	0-10	--	--	16.3	--	8.1	--	(*)	--
Bank 2-140	130-140	--	--	0.17	--	n.d.	--	(*)	--

in stream sediments closely matched those of cultivated, surficial soils in the study area (table 3, fig. 4a). There was considerable overlap in values of suspended versus soil-bound ^{137}Cs activities, although mean suspended ^{137}Cs activities were about one-half the mean activity in surficial soils from cultivated fields (fig. 4b). One sample at each stream site had no detectable ^{137}Cs activitiy. Correlations between suspended excess ^{210}Pb or ^{137}Cs and streamflow (figs. 5b, 5c, 6b, and 6c) or suspended-sediment concentration (figs. 5a and 6a) were not significant ($p>0.05$).

^{7}Be was detected in most suspended-sediment samples, which is a strong indication of inputs of recently eroded surficial soils (table 1, figs 4c, 5d, and 6d).

Table 2. Radioisotope activities in suspended sediments of the Wild Rice River.

[A, activities in millibecquerels per gram dry sediment; σ, counting error of +/- one standard deviation; -, falling stage; ~, stable stage; +, rising stage; n.d., not detected; *, exceeded holding time for ^{7}Be; mean values are based on detected values (means with zero substituted for the undetected values are given in parentheses)]

Date	Stage	Total ^{210}Pb		^{226}Ra		excess ^{210}Pb	^{137}Cs		^{7}Be		^{40}K	
		A	σ	A	σ	A	A	σ	A	σ	A	σ
Wild Rice River at Twin Valley, Minnesota												
3-Mar-98	-	28.5	1.5	19.9	1.9	8.60	2.87	0.78	n.d.		428	13
26-Mar-98	~	50.0	2.2	34.9	4.6	15.1	4.96	1.8	n.d.		578	17
11-May-98	+	66.7	2.6	26.9	2.7	39.8	5.68	2.2	571	68	976	20
13-May-98	+	29.5	1.6	24.4	1.9	5.02	1.93	1.3	122	23	501	15
14-May-98	+	30.7	1.5	23.5	1.9	7.25	6.90	2.3	145	33	501	20
18-May-98	-	32.0	1.6	23.6	2.6	8.43	3.58	1.4	87	29	518	16
19-May-98	-	30.0	1.1	21.6	2.0	8.42	n.d.		n.d.		667	13
27-May-98	-	36.6	1.2	28.2	2.1	8.43	4.31	0.6	42	12	416	12
22-Jun-98	-	29.9	1.1	22.9	3.0	7.07	1.47	0.82	53	11	507	10
25-Jun-98	-	25.5	0.93	19.8	3.2	5.77	2.35	0.85	88	12	408	12
29-Jun-98	-	28.1	1.0	21.2	1.6	6.94	4.48	0.81	92	10	662	13
2-Jul-98	-	31.9	1.1	26.6	2.0	5.34	2.37	1.3	77	19	500	10
9-Jul-98	+	41.6	1.3	30.5	3.8	11.1	6.93	1.2	92	8.2	445	13
14-Jul-98	+	80.1	3.2	16.3	1.5	63.8	11.49	1.3	(*)		285	9
5-Aug-98	-	55.2	3.0	22.2	1.6	33.0	n.d.		(*)		353	7
Mean						15.6	4.56 (3.95)		137 (105)		516	
Standard deviation						16.8	2.75		155		164	
Mean for falling or stable stream stage						10.7	2.90 (2.60)		73.2(48.8)		504	
Mean for rising stage						25.4	6.59		233		541	
Wild Rice River at Hendrum, Minnesota												
25-Mar-98	~	55.8	1.7	34.9	5.0	20.9	5.51	0.88	n.d.		456	14
12-May-98	+	47.7	1.6	28.6	3.6	19.2	2.08	0.56	119	23	837	17
13-May-98	+	46.4	1.6	29.8	2.5	16.5	9.57	1.9	265	40	565	17
14-May-98	+	45.6	1.6	28.7	3.0	16.8	5.38	0.97	105	19	493	15
18-May-98	+	54.8	1.7	36.6	3.4	18.2	8.82	1.2	194	27	489	15
19-May-98	+	51.6	1.3	28.2	4.8	23.4	9.33	1.2	174	38	606	18
27-May-98	-	44.9	1.2	33.4	2.9	11.6	4.35	1.4	43	18	475	14
23-Jun-98	-	38.0	1.2	30.1	3.7	7.9	n.d.		56	20	383	7.7
25-Jun-98	-	50.0	1.3	40.4	4.1	9.6	7.99	0.16	182	18	767	23
30-Jun-98	+	33.2	1.0	25.8	3.7	7.4	3.76	1.5	167	25	637	19
2-Jul-98	-	40.8	1.4	30.5	2.7	10.3	5.02	0.9	111	10	460	14
7-Jul-98	-	46.7	2.3	24.4	2.0	22.3	3.53	1.3	(*)		428	13
9-Jul-98	+	52.2	2.0	35.0	4.2	17.2	6.80	0.88	240	14	482	14
6-Aug-98	-	43.3	2.2	19.5	1.2	23.8	n.d.		(*)		474	9
Mean						16.1	6.01 (5.15)		151(138)		539	
Standard deviation						5.7	2.47		71		131	
Mean for falling or stable stream stage						15.2	4.40 (3.80)		98.0(78.4)		492	
Mean for rising stage						17.0	6.53		181		587	

Table 3. Radioisotope activities in the upper 1 cm of cultivated soils of the Wild Rice River Basin, sampled after autumn harvest and plowing, September-November, 1998.

[A, Activities in millibecquerels per gram dry sediment; σ, counting error of +/- one standard deviation; n.d., not detected; mean values are based on detected values (means with zero substituted for the undetected values are given in parentheses).]

Sample identification	Latitude (North)	Longitude (West)	Total ^{210}Pb		^{226}Ra		Excess ^{210}Pb	^{137}Cs		^{7}Be		^{40}K	
			activity	σ	activity	σ	activity	activity	σ	activity	σ	activity	σ
HO-1-S	47°12'14"	96°06'36"	24.0	0.9	20.6	2.1	3.4	6.9	1.4	11.3	10.3	558	11.2
HO-3-S	47°12'14"	96°06'36"	30.3	1.0	22.0	2.0	8.3	11.0	1.2	n.d.	n.d.	489	9.8
HO-5-S	47°12'14"	96°06'36"	47.4	1.4	24.8	2.2	22.5	14.1	2.1	n.d.	n.d.	746	14.9
KR-1-S	47°05'38"	96°19'27"	22.5	0.9	20.7	2.7	1.7	9.2	1.4	n.d.	n.d.	439	13.2
KR-2-S	47°05'38"	96°19'27"	18.6	0.8	14.9	1.3	3.7	11.0	1.5	n.d.	n.d.	532	16.0
KR-3-S	47°05'38"	96°19'27"	28.0	1.0	12.9	1.2	15.1	5.0	1.0	n.d.	n.d.	382	7.6
KL-1-S	47°04'54"	96°07'45"	25.4	0.9	28.1	2.8	-2.6	6.1	1.6	n.d.	n.d.	707	14.1
KL-3-S	47°04'54"	96°07'45"	34.0	1.1	22.2	2.7	11.8	16.3	2.1	n.d.	n.d.	674	20.2
KL-5-S	47°04'54"	96°07'45"	40.7	1.4	24.3	1.7	16.4	9.5	1.2	n.d.	n.d.	464	9.3
SK-1-S	47°20'27"	96°08'06"	35.6	1.2	18.4	1.1	17.2	10.6	0.8	n.d.	n.d.	423	8.5
SK-2-S	47°20'27"	96°08'06"	31.6	1.1	20.7	2.1	10.9	7.5	1.4	n.d.	n.d.	665	20.0
SK-6-S	47°20'27"	96°08'06"	38.8	1.2	24.1	1.7	14.7	10.5	1.6	n.d.	n.d.	618	12.4
BO-1-S	47°10'45"	96°47'57"	43.8	1.2	30.4	1.5	13.5	13.1	1.0	n.d.	n.d.	749	15.0
BO-3-S	47°10'45"	96°47'57"	44.8	1.4	30.1	1.2	14.7	11.9	0.8	n.d.	n.d.	747	14.9
BU-1-S	47°20'18"	95°59'25"	34.6	1.0	22.9	2.1	11.6	9.3	1.7	n.d.	n.d.	682	20.5
BU-2-S	47°20'18"	95°59'25"	34.4	1.1	21.5	1.5	12.9	10.5	1.3	n.d.	n.d.	629	12.6
BU-3-S	47°20'18"	95°59'25"	42.5	1.5	27.1	1.4	15.4	10.6	1.1	n.d.	n.d.	753	15.1
GE-1-S	47°10'45"	96°33'43"	39.5	1.6	25.7	1.5	13.8	10.8	1.2	n.d.	n.d.	705	14.1
GE-2-S	47°10'45"	96°33'43"	36.7	1.1	24.9	1.5	11.8	12.1	1.3	n.d.	n.d.	544	10.9
GE-3-S	47°10'45"	96°33'43"	44.7	1.2	23.5	1.2	21.2	13.1	1.0	n.d.	n.d.	529	10.6
Mean							11.9	10.4		n.d.	n.d.	602	
Standard deviation							6.3	2.7		n.d.	n.d.	121	

^{7}Be was not detected in suspended-sediment samples collected in March. These samples were analyzed in late July-early August, about 2.25–2.65 half-lives after collection, and it is possible that relatively low ^{7}Be activities would have decayed to less-than-detectable activities during that time. Accordingly, ^{7}Be data for March are not used for analysis of source sediments. The lack of ^{7}Be detections (except 1 sample) in surficial soils collected in the fall can be explained by the post-tillage collection of soil samples, which likely diluted surface-accumulated ^{7}Be to less-than detectable levels in all but one sample. Radioisotope activities and inventories in reference soil cores are given in table 3.

Implications for sediment sources

To assess the relative contributions of surficial soils versus streambank sediments as potential sources of suspended sediment to the Wild Rice River, certain assumptions were made. First, radioisotope activities in the upper 1 cm of surficial, cultivated soils are representative of erodible soils. Second, activities of excess ^{210}Pb and ^{137}Cs are approximately uniform in the plow layer (upper 20 cm), implying that the measured activities may be useful to assess sheet, rill, and minor gully erosion. ^{7}Be, in contrast, is assumed to be concentrated in the upper few mm, and would be greatly diluted by minor gully erosion (gullies greater than a few cm depth). Third, bank erosion is assumed to occur along a vertical plane. Fallout radioisotopes in bank material are detected only in the upper portion (table 1), and thus would be diluted by isotope-free sediment as a vertical section of a cut bank sloughs into the river. The degree to which radioisotope inventories would be diluted is directly related to the height of the bank. Fourth, suspended isotopic activities are assumed to be a mixture of activities found in these potential sources. This is a simplification because radioisotope activities tend to be higher in fine-grained sediments (fines) than in coarser sediments, whereas coarser sediments would be redeposited more quickly than fines (and hence not be collected as suspended load). The samples are thus some-

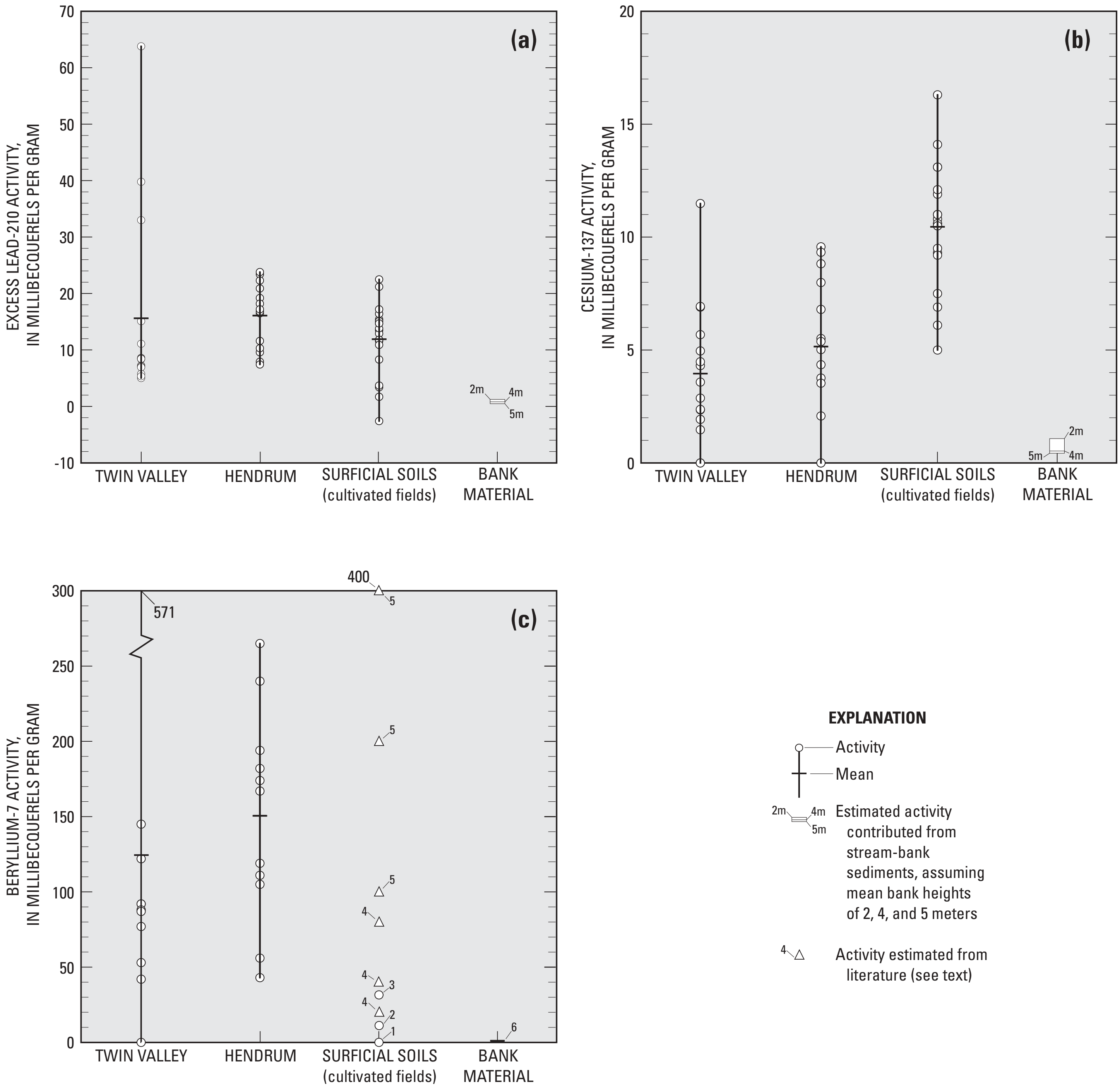

Figure 4. (a) Excess lead-210, (b) cesium-137, and (c) beryllium-7 activities in suspended-sediment samples from the Wild Rice River at Twin Valley, Minnesota and at Hendrum, Minnesota; in surficial soils from cultivated fields; and estimated activities contributed from erosion of streambank material (calculated by diluting reference isotopic inventories with 2 m, 4 m, and 5 m [meters] of bank-material sediments). (For beryllium-7, note the following: surface-soil samples were collected after fall plowing, thereby diluting most values to undetectable levels (note 1); one low level activity was detected (note 2); one value from a reference core (upper 2 cm) is shown (note 3). Estimated ranges of beryllium-7 activities are based on literature deposition rates (see text). For surface soils, steady-state inventories were assumed to be distributed in the upper 1.0 cm (note 4) or upper 0.2 cm (note 5). Dilution of steady-state inventories by bank-material sediments resulted in estimated beryllium-7 activities of less than 0.34 millibecquerels per gram for all bank heights of 2 m or greater (note 6).)

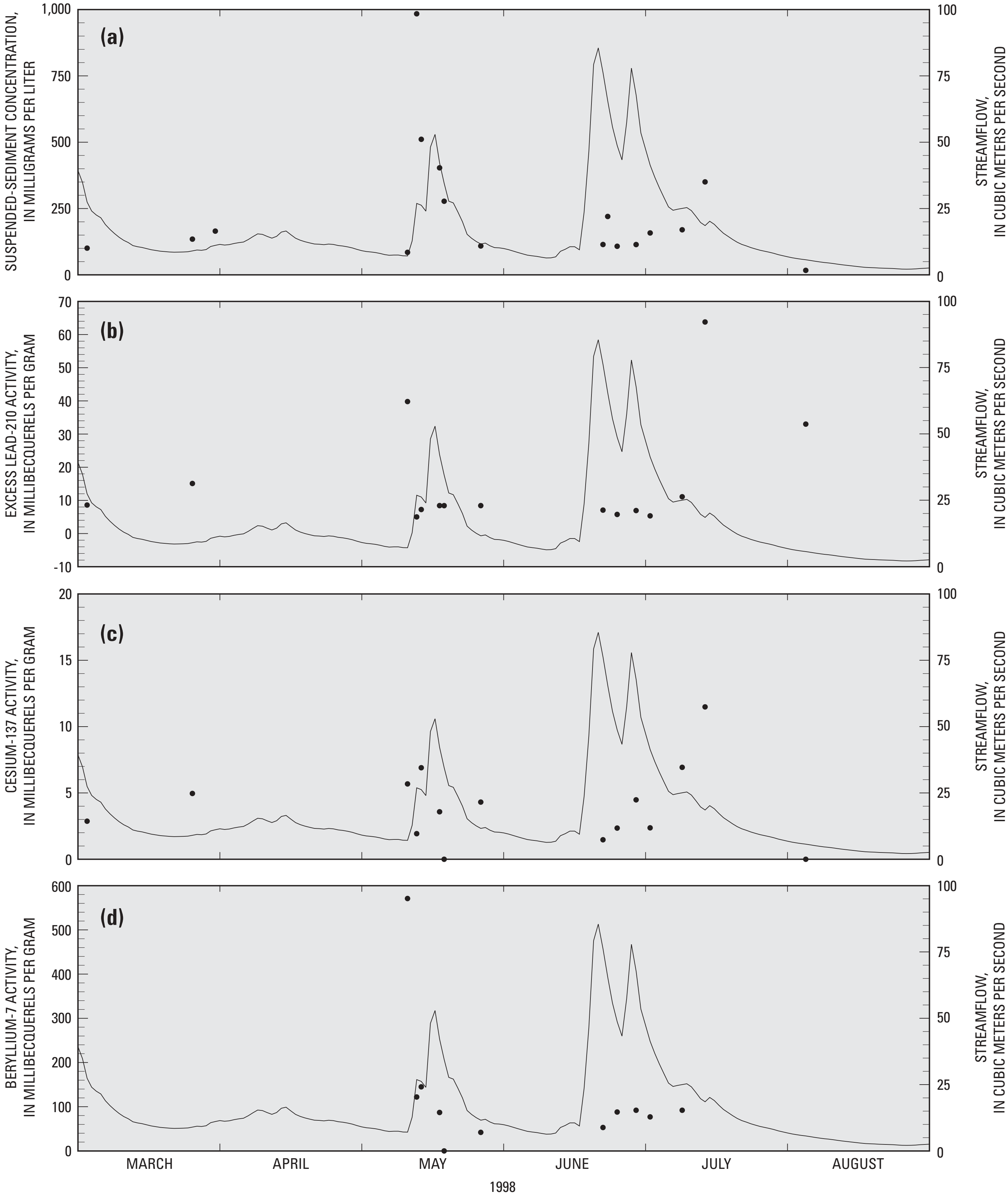

Figure 5. (a)Suspended-sediment; (b) excess lead-210; (c) cesium-137; and (d) beryllium-7 verses time, overlain on hydrograph, for Wild Rice River at Twin Valley, Minnesota, spring-summer 1998.

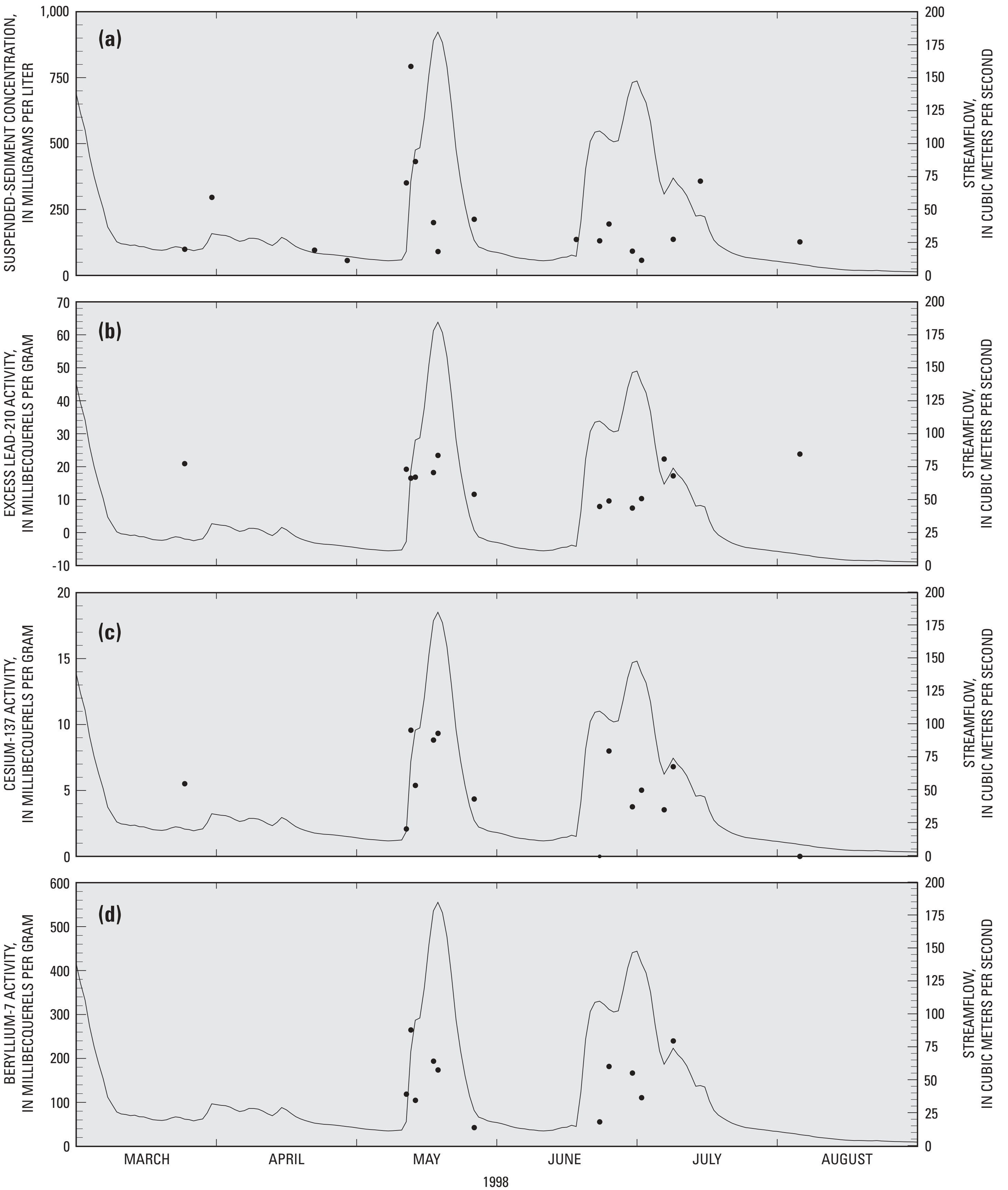

Figure 6. (a) Suspended-sediment; (b) excess lead-210; (c) cesium-137; and (d) beryllium-7 verses time, overlain on hydrograph, for Wild Rice River at Hendrum, Minnesota, spring-summer 1998.

what biased toward fines, relative to sediment sources.

To estimate bank contributions of isotopic activities, reference inventories are adjusted for dilution by an "average" height of erodible cut banks. Typical heights of erodible cut banks range from about 1–12 m, with 4 m being a mid-range estimate for the basin. Dividing reference isotopic inventories by bank height of 4 m (400 cm), and dividing the result by a bulk density of 1.2 g/cm^3, yields estimates of the mean activity that bank-eroded sediment would contribute to the suspended load. Excess ^{210}Pb inventories from the three reference cores yield a mean activity of 0.62 mBq/g for a 4-m bank (fig. 4a). For ^{137}Cs, only cores 5–1 and 3–3 were used (the activity measured for core 6–2 was an outlier), yielding a mean activity of 0.53 mBq/g for a 4-m bank (fig. 4b). These values do not change markedly if other reasonable estimates of mean cut-bank heights are used (for example 2 m and 5 m; see fig. 4).

Although only one ^{7}Be inventory was determined (42 mBq/cm^2, core 5–1, table 1), it agrees with reported depositional rates and measured activities in surficial soils. Todd and others (1989) reported ^{7}Be depositional rates of 12.0–12.9 dpm/cm^2/yr in southeastern Virginia, which convert to steady-state inventories[1] (assuming constant inputs, and accounting for decay) of 42.1–45.3 mBq/cm^2, or a mean of about 44 mBq/cm^2.

Similarly, Baskaran (1995) reported annual rates of 12.00–23.62 dpm/cm^2/yr in Galveston, Texas, which convert to steady-state inventories of 42.1 (drier year) to 82.8 (wetter year) mBq/cm^2.

Steady-state ^{7}Be inventories should typically be lower in northwestern Minnesota than in Virginia or the Gulf Coast of Texas, due to lower annual precipitation in Minnesota. Instantaneous inventories, however, could be relatively high after precipitation events, and decay to lower values during dry periods. Given these caveats, and comparison to literature data, our measured ^{7}Be inventory could underestimate or overestimate typical instantaneous inventories significantly, perhaps by a factor of about 2. ^{7}Be inventories in the Wild Rice River Basin are, therefore, expected to be in the range of about 20–80 mBq/cm^2, with 40 mBq/cm^2 as a mid-range estimate.

Such inventories would contribute ^{7}Be activities of about 40 mBq/g (range of 20–80 mBq/g), if averaged over the surficial 1 cm of soil, assuming a dry-mass density of about 1–1.2 g/cm^3 for surficial soils. For comparison, Walling and Woodward (1992, p. 157) detected ^{7}Be in the upper 1 cm of soil cores from pasture and cultivated sites in Devon, England, with activities ranging from about 6–52 mBq/g (mean for upper 1 cm ranged from about 22–33 mBq/g). Walling and others (1999, p. 3868) reported activities of about 21–80 mBq/g for surficial increments (less than 1 cm depth) of soil cores in Devon, England. Wallbrink and Murray (1996b) reported near-surface (0–4 mm) ^{7}Be activities of about 23–75 mBq/g for soils in Tasmania, and about 30–60 mBq/g in bare surficial soils in Black Mountain, Australia. Because much of the fallout ^{7}Be is contained in the upper few mm of soil, activities in the surface 2 mm (the layer most readily eroded) are potentially higher than activities averaged over the upper 1 cm. Also, inventories and surficial activities are likely much higher directly following precipitation events.

Averaging ^{7}Be inventories over a theoretical 4-m cut bank yields an estimated mean ^{7}Be activity contributed from bank erosion of about 0.08 mBq/g (range of 0.04–0.16 mBq/g), assuming a dry mass density of 1.2 g/cm^3 for the soil column. A mean bank height of 2 m yields an estimated ^{7}Be activity from bank material equal to only 0.085–0.34 mBq/g, suggesting that suspended ^{7}Be activities greater than 1 mBq/g are strongly indicative of upland soil inputs.

The estimates of mean activities of excess ^{210}Pb, ^{137}Cs, and ^{7}Be contributed from bank material (when reasonable estimates of mean heights of cut banks are used) are less than levels that can be reliably detected. This indicates that if bank-erosion is the sole, or dominant source of suspended sediments to the river, then suspended isotopic activities would be undetectable.

A simple mixing model can be applied to measured suspended isotopic activities, assuming two sources of suspended sediments: upland soil and streambank. This model is represented mathematically as:

$$A_{sed,i} = f_{soil}\, A_{soil,i} + f_{bank}\, A_{bank,i} \quad (3)$$

where $A_{sed,i}$ is the activity of isotope i in suspended-sediment samples;

$A_{soil,i}$ is the mean activity of isotope i in surficial soils from cultivated fields (excess ^{210}Pb and ^{137}Cs are means from data in table 2; ^{7}Be is assumed to be 40 mBq/g, as previously described);

$A_{bank,i}$ is the estimated mean activity of isotope i contributed from bank erosion (assuming dilution of isotopic inventories with bank material, as described above);

f_{soil} is the fraction of suspended sediment that originates from soil erosion; and

f_{bank} is the fraction of suspended sediment that originates from bank erosion.

In equation 3, all quantities are measured or estimated except f_{soil} and f_{bank}. The fractions of sediment originating from different sources must sum to 1. Therefore, substituting the quantity (1- f_{soil}) for f_{bank} the equation can be solved for f_{soil}:

$$f_{soil} = (A_{sed,i} - A_{bank,i}) / (A_{soil,i} - A_{bank,i} \quad (4)$$

The quantity f_{bank} can be solved similarly or, as noted above, $f_{bank} = 1 - f_{soil}$. It follows that an f_{soil} value of 1 indicates that soil erosion contributes all suspended sediment to the stream, whereas an f_{bank} value of 1 indicates that bank erosion contributes all suspended sediment to the stream. Values of f_{soil} greater than 1 may result (and, hence, f_{bank} values are forced to negative values) when stream sediment samples have higher isotopic activities than the mean values measured (or estimated, for ^{7}Be) in surficial soils, which indicates it is possible that a third source of suspended sediment (with high isotopic activities) exists. Because this is consid-

[1]Steady-state inventory (I) is the total amount of radioisotope under a specific area. I = F/k, where F = fallout rate (in mBq/cm^2/yr), and k = radioactive-decay rate constant (in yr^{-1}). For ^{7}Be, k = 4.75 yr^{-1} ($k = [\ln(2)/t_{1/2}]$, where ln is the natural logarithm function and $t_{1/2}$ is the half life of ^{7}Be in years (53.3 d, or 0.1459 yr). The steady-state assumption is an oversimplification, because inputs of ^{7}Be vary seasonally, and the half life is much less than 1 yr.

ered unlikely, for summary purposes (table 4), all *f*-values that exceed 1 were set equal to one; accordingly all *f*-values that were less than zero were set equal to zero. This adjustment keeps *f*-values within their physically meaningful domains (0–1), and precludes one or a few extreme values from biasing the mean.

Model-estimated values of f_{soil} and f_{bank} vary considerably among sediment samples collected during spring-summer 1998 (fig. 7 and 8). Consistent with the patterns in activities, the downstream site (Hendrum) tended to yield higher values of f_{soil} (table 4), indicating that a greater fraction of suspended sediment in the downstream portion of the river originates from soil erosion, compared to upstream of Twin Valley, where bank erosion appears to be of greater relative importance.

Values of f_{soil} determined from excess ^{210}Pb and ^{7}Be tend to indicate predominantly erosion of surficial soils, whereas ^{137}Cs indicated more of a mixed source, with bank material being of somewhat greater importance than soil erosion. The reason for this disagreement is unknown. A possible explanation is that there are upland soil areas that contribute sediment to the stream that have been partially depleted of ^{137}Cs, through erosion, that are underrepresented in our sampling. More actively eroding areas could be disproportionately depleted of ^{137}Cs, compared to ^{210}Pb and ^{7}Be, because ^{137}Cs was mainly a pulse input in the 1960's, whereas ^{210}Pb and ^{7}Be inputs are relatively constant over time. This discrepancy highlights the importance of obtaining multiple indicators of sediment sources, rather than relying on a single indicator.

Activities of fallout isotopes tend to be greater when stream stages are rising, compared to falling or stable stages (table 2). Accordingly, f_{soil} values (particularly for excess ^{210}Pb and ^{137}Cs) tend to be greatest during rising stages, whereas f_{bank} values tend to be greatest during falling stages (figs. 7 and 8). This pattern, although somewhat variable and based on limited coverage of a range of flow conditions, is consistent with the concept that the greatest soil-erosion rates should occur with large (runoff-producing) rain events, whereas the greatest bank-erosion rates should occur when streambanks may be more saturated and stage is decreasing.

CONCLUSIONS AND LIMITATIONS OF STUDY

This study provides evidence that upland soil erosion from cultivated fields contributes the majority of the suspended-sediment load in the Wild Rice River. Therefore, efforts to control or minimize upland soil erosion will likely reduce instream suspended-sediment concentrations. Bank erosion also contributes to the suspended-sediment load, although ^{210}Pb and ^{7}Be data indicate that bank erosion is not the dominant source of suspended sediment. Efforts to minimize bank erosion may help reduce suspended-sediment concentrations, but might not be as effective as controlling upland soil erosion.

This study applied fallout radioisotope techniques, which have traditionally been applied in very small areas such as single farm fields, to a larger basin (4,038 km^2). Accordingly, sampling was distributed over a large area, and source-soils were not characterized in great spatial detail. Suspended sediments sampled for radioisotope analysis were collected over a limited time frame and were targeted toward runoff events, when suspended-sediment concentrations tend to be greatest. Isotopic activities of suspended sediments during base flow, when suspended-sediment concentrations tend to be low, are represented by few samples. Also, data collection for this study was focused on determining sources of suspended sediments; the data are not useful for inferring the quantity or predominant source of bedload sediments. Bedload, typically composed of coarser sediments than suspended sediments, is thought to be important in streams draining glaciofluvial sediments. It is possible that bank erosion, although not the dominant source of suspended sediments, is an important contributor to bedload and to channel-forming processes (point bar migration, and so forth.).

Fallout radioisotopes were useful indicators of sediment sources in the Wild Rice River Basin, and may be useful in other relatively large basins. Additional studies may provide a more detailed characterization of source areas, and suspended isotopic signatures over a greater range of basin types and hydrologic conditions. It may be useful, for example, to assess suspended radioisotope levels in contrasting basins—a basin where severe bank erosion is thought to predominate; a basin where both soil and bank erosion may be prevalent; and an agricultural basin where bank erosion is minimal. Suspended radioisotope levels would be expected to increase along such a gradient; such data may confirm the utility of the method for determining sediment sources in streams where the dominant source is in doubt.

Table 4. Fraction of suspended sediment originating from soil erosion (f_{soil}), as determined from excess lead-210, cesium-137, and beryllium-7 activities in sediments and source areas (surficial cultivated soils and bank material).

[Values of f_{bank} are equal to 1-f_{soil}.; *f*-values of zero result when the isotope was not detected (n.d.) in a sample; *f*-values greater than 1 (or less than zero) were set to 1 (or zero); the quantity $f_{soil,mean}$ is calculated from mean f_{soil} values for each isotope.]

	Twin Valley			Hendrum		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
$f_{soil,Pb-210}$	0.39	0.71	1.0	0.60	0.92	1.0
$f_{soil,Cs-137}$	0 (n.d.)	0.34	1.0	0 (n.d.)	0.47	0.91
$f_{soil,Be-7}$	0 (n.d.)	0.91	1.0	1.0	1.0	1.0
$f_{soil,mean}$(all isotopes)		0.65			0.80	

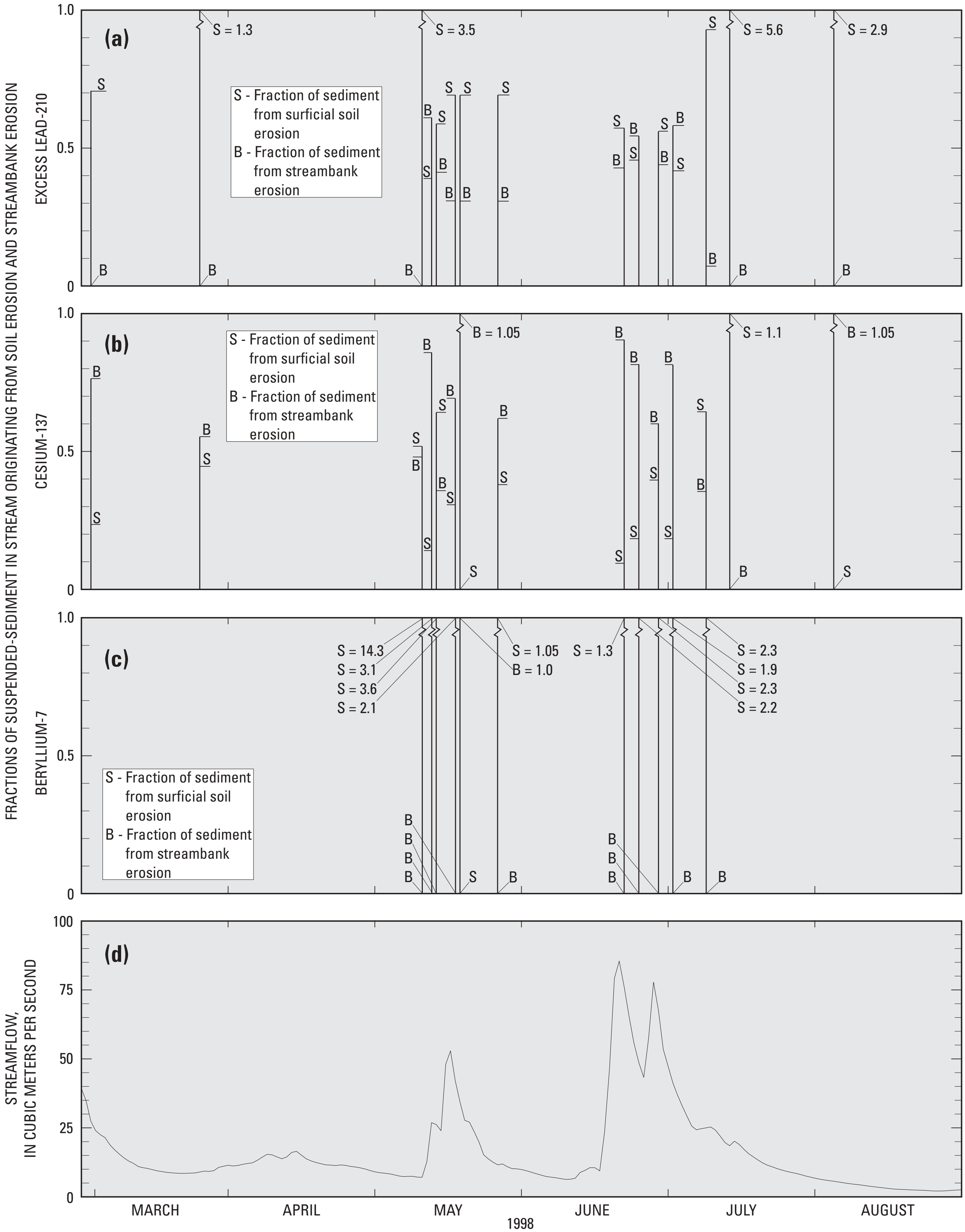

Figure 7. Model estimates of the fraction of suspended-sediment in the Wild Rice River at Twin Valley, Minnesota, that originates from erosion of surficial cultivated soils and by vertical erosion of streambank material, determined from (a) excess lead-210; (b) cesium-137; and (c) beryllium-7, (For bank sources, the model assumes dilution of reference activities by 4 meters of bank-material sediments), and (d) stream hydrograph.

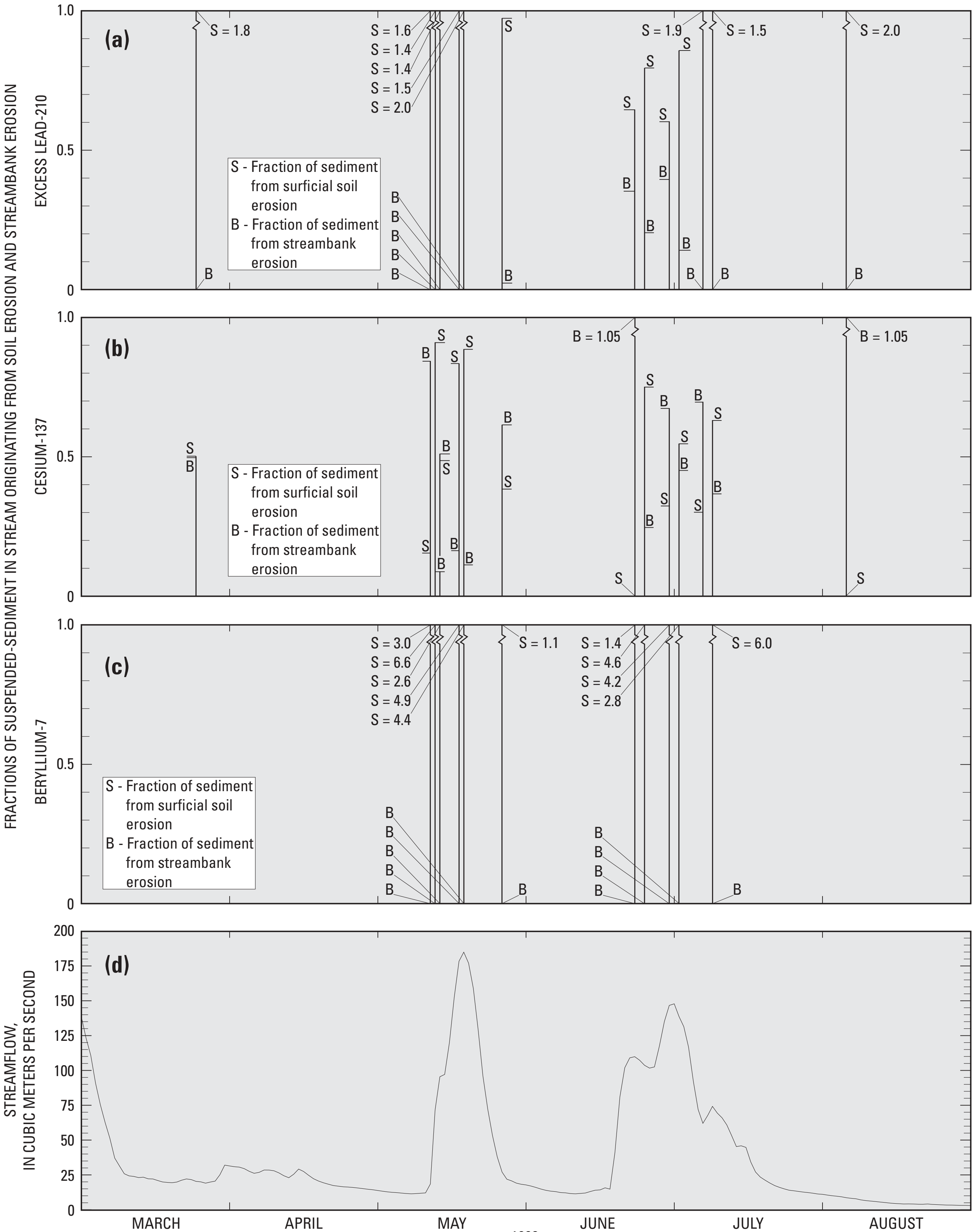

Figure 8. Model estimates of the fraction of suspended-sediment in the Wild Rice River at Hendrum, Minnesota, that originates from erosion of surficial cultivated soils and by vertical erosion of streambank material, determined from (a) excess lead-210; (b) cesium-137; and (c) beryllium-7. (For bank sources, the model assumes dilution of reference activities by 4 meters of bank-material sediments.), and (d) stream hydrograph.

SUMMARY

Sedimentation is a significant resource concern in the Red River of the North Basin (RRB). The Wild Rice River, a tributary to the Red River of the North, and its drainage basin were studied to assess sediment concentrations, loads, and potential sources of suspended sediment. We examined historical suspended-sediment data and activities of fallout radioisotopes (lead-210 [^{210}Pb], cesium-137 [^{137}Cs], and beryllium-7 [^{7}Be]) associated with suspended sediments and source-area sediments (cultivated soils, bank material, and reference soils) in the Wild Rice River Basin to better understand sources of suspended sediment to streams in the region.

Multiple linear regression analysis of suspended sediment concentrations measured from 1973–98 (Wild Rice River at Twin Valley, Minn.) exhibit the following: strong dependence on streamflow; limited seasonal dependence, with flow-adjusted concentrations slightly higher in the spring than summer-autumn; and no significant temporal trend. Suspended-sediment load estimates were developed for the Wild Rice River at Twin Valley, Minn. and at Hendrum, Minn., based on 913 and 35 samples, respectively. The mean loads for 20 years of data (1973–84; 1989–98) were 31,500 and 60,000 metric tons per year, respectively, for the two sites. Relatively low net rates of upland soil erosion (about 2.2–2.5 millimeters [mm] of soil per century) could support these suspended loads; similarly, moderately high rates of net stream-bank erosion (about 3.7–15 meters per century of horizontal erosion of vertical cut bank) could account for the entire suspended load. In both cases, net erosion is thought to be a small percentage of total erosion, due to redeposition in the upland (soil only) and riparian (soil and bank sediments) environments.

Activities of the fallout radioisotopes ^{210}Pb, ^{137}Cs, and ^{7}Be were measured in samples of suspended and source-area (soil, reference, and bank material) sediments during spring-summer 1998. The fallout radioisotopes were nearly always detectable in suspended sediments during spring-summer 1998. Mean ^{210}Pb and ^{7}Be activities in suspended sediment and surficial, cultivated soils were similar, perhaps indicating little dilution of suspended sediment from low-isotopic-activity bank sediments. In contrast, mean ^{137}Cs activities in suspended sediment indicated a mixture of sediment originating from eroded soils and from eroded bank material, with bank material being a somewhat more important source upstream of Twin Valley, Minnesota; and approximately equal fractions of bank material and surficial soils contributing to the suspended load downstream at Hendrum, Minnesota. In general, ^{210}Pb and ^{7}Be data indicated that suspended sediments originate primarily from upland soil erosion, whereas ^{137}Cs data indicated a mixed source, with streambank sediments slightly more important. Application of fallout radioisotopes appears to be a useful tool to resolve ambiguity in cases where the dominant source of sediments—upland soil erosion or stream-bank erosion—is unknown, and both sources are thought to contribute. This study indicates that, to be effective, efforts to reduce sediment loading to the Wild Rice River should include measures to control soil erosion from cultivated fields.

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